THE EFFECTS OF SONIC VIBRATIONS ON INJECTOR CHARACTERISTICS OF LIQUID PROPELLANT ROCKETS

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SUMMARY

Rocket instability is not very well understood in liquid propellant rockets. Propellant vaporization is one rate controlling process in the combustion process. The object of this investigation was to investigate the effect of sonic vibrations on liquid drops in sprays and liquid jets.

Difficulties were encountered in obtaining a suitable source that would give high intensity sonic vibrations. A loudspeaker unit was used to drive a resonant tube. The effects on liquid jets were photographed and interpreted. High speed photography was employed to observe the phenomena.

ACKNOWLEDGMENT

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CONTENTS

GENERAL DESCRIPTION OF THE COMBUSTION PROCESS IN A LIQUID PROPELLANT ROCKET

Consider a rocket chamber into which a combination of propellants such as kerosene and liquid oxygen are introduced. Reaction will only occur in the vapor phase of both propellants. To make the best use of the chamber the propellants must be uniformly distributed in the chamber. If the chemical reaction is to be as efficient as possible mixing of the propellants must be complete and uniform. Assuming both propellants are liquids they must be vaporized and ignited. In order to make use of all the energy available to produce thrust it is desirable that the reaction be completed within the chamber using stoichemetric proportions of the propellants.

Two types of injectors used for such a bi-propellant system are impinging jets and showerhead type injectors with alternate atomizers introducing kerosene and oxygen. The liquids are atomized in order to expose a large surface area for rapid vaporization.

Initial ignition may be accomplished by a pyrotechnic squib or a spark. Continuous ignition is maintained by recirculation and diffusion of hot gaseous products of combustion.

The reaction of the two liquids result in the generation of heat and gaseous products of combustion. This expansion process rapidly accelerates the gases in the chamber toward and through the nozzle of the rocket. The expulsion of the gases produces the thrust.

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In the use of self-igniting bi-propellant systems such as nitric-acid and unsymmetrical dimethyl hydrazine it is normal practice to use impinging jets of unlike liquids. Flames occur rapidly upon contact. A certain amount of mixing and reaction is accomplished in the liquid phase but the liquids are thought to be largely vaporized prior to reaction with mixing and reaction occurring mostly in the vaporized state. Nevertheless these processes of vaporization, mixing, and ignition are facilitated.

The use of a monopropellant such as nitro-methane makes mixing unnecessary. However atomization, vaporization, distribution, and ignition are necessary.

One of the approximations used in the analyzation of the combustion process in constructing a model is that the reaction takes place instantaneously. Thus, in an idealized model a source or sources of heat and gas can be assumed at a certain axial location in the combustion chamber. In reality the combustion process is a gradual one. There is a time lag between injection and reaction or ignition. This time lag may be thought of and expressed as a space lag (see figure 1). In an actual rocket there is much turbulence in the combustion chamber. Due to this turbulence, variations in vaporization and reaction rates, there is a variation in time lag for various elements of propellants. In fact the physico-chemical processes during combustion in rocket engines is so complex it is very nearly impossible to give a quantitative description of them ~~(see figure 3)~~.

/In

In recent years there have been a number of experimental and theoretical studies carried out on the burning characteristics of drops and fuel sprays. In general vaporization is proportional to the surface area or for a drop:

$$D^2 = D^2_o + K't$$

where D_o is the initial drop diameter, D is the diameter at time, t, and K' is the evaporization constant. The evaporation constant is independent of the diameter and is defined by the relation:

$$K' = 4\dot{m}_f/\pi D \rho_l$$

where $\dot{m}_f$ is the mass burning rate of the fuel and ρ_l is the density for a droplet of diameter D.

Much work has been done on laminar flames. However the useful flames encountered in a combustion chamber are turbulent and thus far there is little theoretical work concerning turbulent flames.

In reference 18, C.C. Miesse discussed combustion of a liquid fuel spray. He investigated the effect of atomization on combustion. His assumptions were: 1. that the propellants react only in the vapor state, 2. that the propellant vapors react as a single chemical substance, implying that perfect mixing is effected immediately upon vaporization of the spray, and 3. that the system was isothermal. In this report Miesse shows how atomization effects the burning rate and how performance varies with burning rate and atomization.

He also found that the assumption made by some concerning diffusion flow of oxidizer vapor in toward the fuel droplet leads

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to a constant flame drop radius ratio, is not verified by experiment. He found that flame drop radius ratio decreases with the diameter of the drop.

Wiesse concluded that the performance of a liquid propellant rocket is dependent upon two dimensionless groups which are equal to the product of the reaction frequency (reaction rate) and gas residence time or droplet lifetime. An increase in either of these leads to higher performance.

Priem and Heidmann in reference 19 calculated vaporization rates for five different propellants as sprays in a liquid rocket chamber. For injectors for which drop size could be calculated combustor lengths calculated were in very good agreement with experimental results. Variations in performance could be explained by variations in percent of propellant vaporized. Their results indicate that combustor efficiency can be predicted from a model based on propellant vaporization as the rate controlling process.

INSTABILITY IN A LIQUID PROPELLANT ROCKET

Experimental observations of combustion in liquid rockets have shown that the process is always rough or, using another term, turbulent. Reaction is rapid and intense heat is generated. If the severe turbulence is random the process is termed "smooth combustion". The noise involved in smooth combustion is termed "white noise". If by some means some frequency is amplified the combustion is termed "rough". In some instances of rough combustion the amplitude of pressure fluctuations reaches a maximum and stabilizes so that the operation of the rocket may not be seriously impaired. In other cases the rough combustion may be unstable to such a degree that the rocket is burned out or caused to fail due to failure of some structural part, the feeding system, or the controls.

Random turbulence and turbulent combustion is desirable in a rocket. Continuous ignition and the high reaction or burning rates required would not be possible without the severe turbulence.

One form of rough combustion or instability is termed "chugging". Chugging refers to frequencies less than 100 cycles per second. It is thought to be caused by resonance in the feeding system and often couples with the oscillations in the chamber. Chugging can be disastrous. Resonance in the feeding system means fluctuating fuel pressures and therefore regular variations in fuel mass flow rates. Chugging can occur due to resonance in the chamber itself without coupling with the feed system. At these low frequencies resulting peak pressures and temperatures are often great enough to burn out

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the rocket combustion chamber. This type of instability can usually be prevented with proper design. However, in increasing the size of a rocket, scaling factors are complex and it is extremely difficult to use performance data from a smaller rocket to design a large one.

For oscillations from 100 cycles per second to several thousand the term "screaming" is used. Due to the high inertia of a liquid propellant as compared to that of a gas or vapor it is unlikely that screaming in a combustion chamber will couple with vibrations in the feeding system. Screaming may lower the performance of the rocket or, if severe enough, cause failure of the rocket.

There are many reports on studies and experiments concerning vaporization of droplets and fuel sprays, and burning rates of fuels. However most of the reports concern studies of evaporation rates and burning in still air or very low turbulence. The mechanics of unstable combustion in a liquid rocket chamber is extremely complex involving many variables.

Linearized perturbation analysis shows that random disturbances in a combustion chamber can be separated into three modes that in first order approximations are independent of each other. These are: (1) a pressure mode (random sound), (2) a vorticity mode (eddy turbulence), and (3) an entropy mode (temperature and density fluctuations). The interaction of these modes is very complex and not very well understood today.

Figure 17 (28 pictures on three sheets) is a reproduction taken from a Rocketdyne report on unstable combustion (see reference 25).

Reference 25 indicates that high-frequency instability requires a "triggering" action and ignition is often the trigger. If during ignition there is not sufficient energy to ignite all the combustibles, the part of the mixture not ignited tends to accumulate in some area of the chamber. When finally ignited it will then form a small explosion. This explosion may start a detonation which will propagate through the rest of the already burning propellants and thus triggers instability.

EFFECTS OF NOISE ON LIQUID JETS AND LIQUID DROPS

Reference 15 gives a fairly complete treatment of sound and related vibrations. In volume II the behaviour of jets of liquid issuing from an orifice in a flat plate under pressure is discussed.

At low velocities a laminar jet of liquid breaks up into drops by a mechanism referred to as varicosity. The stream develops small bumps along the length of it. Surface tension finally causes the stream to break up into near uniform drops, the diameters of which are equal to the diameter of the jet (see figure 4).

A laminar jet of liquid issuing from a sharp edged circular orifice can be thought of as a cylindrical column of fluid held in shape by surface tension forces. Velocity of the fluid times the cross sectional area is a constant. Any disturbance will cause the column to develop waves. These waves will be standing waves. They will appear stationary in relation to the orifice so long as the flow rate os constant. The wave length of these fluctuations is determined by the pressure drop across the orifice.

Any irregularity in the orifice will be accentuated by the jet. An elliptical orifice will cause a wave to form. The fluid will first form into a circular cross section. The cross section will then become elliptical again with the major axis lengthened, and rotated 90° to the major axis of the orifice. This process will repeat itself and the stream approaches a flat sheet of fluid. The velocity of the jet for a certain elliptical orifice will determine whether the jet forms drops by varicose growth of drops, or from sheets of

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fluid. If the velocity is relatively high the first accentuated ellipse will be a sheet of fluid and break up into drops.

A regular polygon of three sides or more forming an orifice will form a number of sheets equal to the number of sides and the sheets will form in planes perpendicular to the sides of the polygon. This action is dependent on the velocity of the jet.

In order to obtain a solid column, or jet, of fluid the orifice must be sharp edged. If not, the jet will be slowed in the boundary layer due to friction. The resulting velocity profile across the jet will not be constant and turbulent flow will result with drops forming rapidly. The size of these drops is originally determined by the size of the jet. However the stability of the large drops formed will depend on the velocity of the jet through the air or gases.

The effect of sound on the jet and drops will depend on frequency and amplitude. If the wave length of the sonic vibrations is equal to or smaller than the diameter of the jet the jet will form drops much quicker. Drops whose diameters are equal to or smaller than the wave length of the sound will be unstable and rapidly break up into smaller drops. If the wavelength of the sonic vibrations is large the break up of the jet, and drops, will be due to friction between the fluid and the air due to velocity fluctuations.

In reference 17, Richard J. Priem describes the effect of shock waves upon liquid jets and drops. He found that the break up of

jets and drops was a function of the relative gas velocity. In the passage of a single shock wave the shock had little immediate effect except to slightly flatten the stream or drop. A series of photographs taken with a high speed camera are in the report. They show this effect and the greater effect of the high velocity gases behind the shock wave. The high speed gases rapidly and gradually distort the jet and break up drops above a critical size depending on relative velocity. Gas velocities of 270 feet per second are reported to break up drops above 150 microns in diameter. At 80 feet per second the critical size of the drops is 600 microns. As would be expected the shock had the greatest effect when acting perpendicular to the flow direction due to the greater area exposed for a unit mass acted upon. Priem reported that the effect of shocks upon impinging jets and the liquid sheets formed was to ruffle the sheet and ligaments extending from it. The effect was not extreme even when the shock was perpendicular to the sheet. However, a reflected shock passing three thousandths of a second later broke the ruffled sheet and drops into a fine mist all the way back to the point of impingment. The pictures in the report indicate the second shock is very effective, whether the shock is perpendicular or parallel to the sheet.

In a second series of pictures the point of impingement is much closer to the wall reflecting the shock. The effect of the second shock is much diminished indicating the duration of the high velocities behind the original shock acting on the sheet of liquid was important.

/Priem

Priem reports three stages of breakup: (1) Development of surface disturbances, (2) Air friction and pressure on pure liquid to produce ligaments and drops, and (3) break up of the ligaments or large drops by relative air flow.

Reference 17 determines drop size distribution data for n-heptane sprays produced by pairs of 90° impinging jets in airstreams over ranges of orifice diameter, D_j, the liquid jet velocity V_j, and velocity difference between the airstream and liquid jet $\triangle V$. The effects of orifice diameter, liquid jet velocity, and the velocity difference between the liquid jets and airstreams on the volume mean drop diameter D_{30} are given in the report as:

$$D_j/D_{30} = 2.64 \sqrt{D_j V_j} + 0.97 D_j \triangle V.$$

D_j and D_{30} are expressed in inches and the velocities in feet per second.

$$D_{30} = (\leq nD^3/\leq n)^{1/3}$$

where n is the number of drops in a given size range, $\triangle D$.

In reference 16, R.P. Fraser compares methods of atomization. He concludes that for swirl spray inkectors flow is proportional to (injector diameter)$^{2/3}$ for constant liquid pressure. For constant injector size flow increases proportional to the square root of the pressure and drop size decreases proportional to the square root of the pressure.

Fraser discusses twin-fluid atomizers in which a high velocity gas stream is made to impinge on the liquid either externally or within the body of the atomizer.

/Noise

Noise may also affect evaporation. In reference 23 it was reported that high frequency fluctuations increased the evaporation rate for cumene by 50% at standard temperature and pressure. The frequencies were ultrasonic. The drop tested was large and was suspended on a screen.

The explanation for the high increase in evaporation rate had to do with agitation of the surface of the large drop. Under a microscope the drop was reported to show visible agitation on the surface. It is probable that turbulence in small local areas around the drop accelerates evaporation by rapidly carrying the vapors formed away and by keeping the surface of the drop free of the insulating effect of a film of 100% vapor.

EXPERIMENTAL PROBLEMS AND SOLUTIONS

The initial object was to experimentally determine what effect, if any, intense sonic air vibrations had on jets and drops at atmospheric conditions. The design and construction of a rig to produce a jet or spray was not difficult.

An empty nitrogen bottle of about 3.5 cubic feet displacement capable of holding nitrogen at 1800 p.s.i. was used as a pressure source. A full nitrogen bottle was connected through a 10 to 1 pressure reducing valve to the empty bottle. An old aircraft pressure bottle of approximately 2 gallon capacity was used as a fuel tank. One quarter inch copper tubing was used to connect the pressure source through a valve to the fuel tank. One quarter inch copper tubing connected the fuel tank to a standard fitting in which a circular flat plate was fitted with a sharp edged circular orifice in it. A fuel filter and a quick acting on-off valve was inserted in the line between the fuel tank and the orifice. Two pressure gauges were fitted. One read pressure on the pressure source and the other read the pressure at the fuel tank.

Three sizes of orifices were used, i.e. .010, .015, and .050 inch diameters. The capacity of the pressurizing system was large enough that the drop in pressure during a short run was considered insignificant. One swirl type atomizer was used with an orifice .015 inches in diameter. An oil drum with the top cut out was used to catch the fuel (water) issuing from the jet (~~see figure 5)~~.

/SOUND SOURCE

SOUND SOURCE

The problem of producing intense sonic vibrations in the manner desired was more difficult. If possible a standing wave was desired. In this way it could be more reasonable to believe that any effect on the jet or spray would be due to the sound and not due to relative air velocity of a stream of air as may come from a siren. The siren is one of the best means of producing intense sound at the frequencies desired.

Reference 15 mentions production of sound using a "singing flame". Some simple experiments were carried out using a bunsen burner and a two foot length of copper pipe. If a bunsen burner with a metal grid flame holder is adjusted to give a flat flame and a pipe is lowered over the flame a load noise or sound will result. Attempts were made to increase the output by matching the resonant tube to the feed tube, but this was not very successful. When the gas in the feed tube appeared to resonating in phase with the air in the resonant tube the flame on the bunsen burner was extinguished. In addition the flow of hot air through the tube was considerable.

If a wire screen is placed in a resonant tube about the one quarter length position and heated until it is red hot, the tube will emit a load sound as it cools. The tube must be in some position other than horizontal so that air flow is induced by heating. The air is given an impetus as it passes up through the screen due to heating. As the flow changes and passes in the opposite direction, hot air flows past the hot screen and no impetus is given to the air.

/As

As to how the sonic fluctuations start it is difficult to say. Nevertheless, a load sound is emitted. The mechanism appears to be the same for the singing flame. Perhaps the flames and the cooling wire screen are the source of the sound amplified by the resonant tube. The length of the tube and the position of the flames or wire determine the frequency.

Reference 24 describes a water hammer device for use as a mechanical means of obtaining large amplitudes at the frequencies desired. Such a device would be large and heavy.

The feasibility of using an ordinary loudspeaker did not seem likely. It was found however that by removing the horn from a speaker and replacing it with a resonant tube, large amplitude standing waves could be realized. When the frequency of the diaphragm of the speaker was tuned to the resonant frequency of the tube the output was noticeably increased. A Tannoy Type SD-5 speaker was fitted with an 8.1 inch resonant tube. The speaker was connected to an electronic oscillator and amplifier. The sound produced did cause a jet of water to deflect and form what appeared to be a sheet of large drops (see figure 5).

It was soon discovered that the capacity of the speaker was not limited by the maximum power fed to it. At resonance frequency for the resonant tube the coil of the speaker pulled away from the diaphragm it was moving. This was overcome by securing the coil to the diaphragm with a stronger cement than that used by the manufacturer.

/An

An improvement was made to this arrangement by placing a cap over the open end of the resonant tube and cutting a 1/4 inch slit in the end of it one inch long. The tube then acted as a helmholz resonator, and produced a resultant pulsing flow of air. Air flowing out of the tube formed a jet in the shape of the slit. When the flow reversed and entered the slit the air rushed in from all directions. Using a pitot tube and a water manometer, 3.5 inches of negative water pressure was measured at the edge of the slit and 3.1 inches of positive pressure was measured in the pulsing stream of air close to the slit. This was at a frequency of 500 cycles per second. In the plane of the slit the average pressure was zero.

By placing 1/2 inch metal guides on either side of the slit the static pressure measured with the pitot tube was nearly zero, while 2.5 inches of positive pressure was measured in the pulsing stream outside of the metal guides, and 3.1 inches of negative pressure was measured at either end of the slit.

By directing the jet of water between the two metal guides the positive and negative fluctuations were nearly equal. This then was nearly a standing wave. The effect on a jet of water was considerable.

Measuring the intensity of the sound accurately is a problem that is solved by the aircraft industries by using an expensive condenser microphone and electronic equipment. It is possible to design a relatively simple piece of equipment that should be adequate.

/A

A suggested device would consist of a pitot tube, a manometer, and an air chamber. Mount the pitot tube in a tight chamber with the tip of the pitot tube centered in a small hole in the chamber. Connect one end of the manometer to the chamber and the other end to the pitit tube. The pitot tube should read only positive velocity fluctuations (see figure 2).

PHOTOGRAPHY

Photographing the phenomenon is not difficult once a technique is established. It was desired to resolve droplets if possible. According to reference 22 the equipment needed would be a point source of light, a lens, and some fast film. Fortunately there existed in the Propulsion Department a spark generator ideally suited for this application. The duration of the spark was less than two micro-seconds. The Photographic Department furnished a lens with a 12-inch focal point and a fast fine grain film (Kodak Commercial Ortho 8 ASA).

It was relatively simple to locate the spark at the focal point of the lens and thereby obtain parallel light. The pictures taken were disappointing. Some were very good, but many had double images and strange shadows. At first this was blamed on the spark. Much better results were obtained by placing the spark about 28 inches from the jet or spray and the film 2 inches from the jet or spray, and doing away with the lens altogether. Shadowgraphs obtained in this way were clear and resolution was good.

A high speed Fastax camera was used to obtain moving pictures of the phenomenon. The Fastax is capable of speeds up to 8000

/frames

frames per second. After three unsatisfactory attempts a technique was established that gave good results.

A General Electric flood lamp was focused through the 12-inch focal length lens on the plane of the camera lens focal point and positioned so that the element of the flood lamp fell across the lens of the camera. By looking in the camera eye-piece one could ascertain when the lens was flooded with uniform bright light. In order to obtain sharp pictures it was necessary to insert into the camera a metal piece with a slit in it that cut the size of the picture to 1/3 its normal coverage. Figure 9 A and B show the effect of this slit. Camera speed used was 4500 frames per second. Good results were obtained with Ilford Pan-S, 24ASA film and Kodak X, 80ASA film.

RESULTS

The photographs of figures 3 and 4 confirm the nature of droplet formation in a stream of fluid as outlined in reference 15.

Figures 6 through 13 are graphic evidence that sonic vibrations do effect a stream of water. Figures 7, 8, 9, 10 and 13 give an indication of the mechanism of this effect. At the frequencies used, the velocity fluctuations are strong enough to bodily move the stream. At peak velocity it is enough to break the larger drops in the stream into smaller drops and ligaments due to friction of the air.

Figure 8 shows that transverse velocity is imparted to a solid stream at the end of the resonant tube which spreads the stream and allows its own velocity differential with the surrounding air to

/disrupt

disrupt it and cause break up.

DISCUSSION AND FUTURE POSSIBILITIES

Figure 12 is a series of high speed photographs of a pair of impinging jets with sound at a frequency of 490 cycles impressed on one of the jets. Although not clear in the photos, the effect was to cause the jets to miss one another at intervals so that pulses of solid stream did not impinge.

The results obtained are not surprising in view of reference 15 and other reports. However, the magnitude of the effect on a jet of fluid was more than was expected. The effect on drops and jets in a combustion chamber may well be much greater.

As a possible future first step it may be interesting to observe the effect of a second sound source on the jet and drops after they have been disrupted by the first one. A sound wave impressed on the stream 90° to the first may produce fairly uniform drops. The phenomenon observed in the photographs in this report appear to be in one plane. Actually, the sound had a tendency to spread the stream, or flatten it in a plane perpendicular to that of the photographs.

The use of two resonant tubes as helmholz resonators with the tubes end to end and connected by parallel flat strips of glass could amplify the effect observed in the photographs of this report. The two speakers used would be operated at identical frequencies 90° out of phase. A stream of water directed between the two pieces of glass would pass through a standing wave of sound.

/Since

Since it is definite that sonic vibrations can effect a stream of fluid and large drops, it may be worth-while to build a pressure chamber in which sonic vibrations could be impressed on a stream of fluid and drops. High pressure and temperature of the atmosphere into which the stream of water is flowing may have a large effect on the action.

From Reference 17 and others, it appears that for a certain relative air velocity there is a certain critical size for drops above which air friction will gradually and rapidly break up the drop into subcritical drops. It is not unreasonable to believe that proper use of sonic vibrations might well be used to atomize fuels and assure a uniform drop size. If not uniform, at least assure a certain maximum drop size.

To investigate effects of sound on evaporation rates, a volatile liquid such as ether could be used. Drops at a certain distance from the injector could be compared with and without sound by the use of photography.

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CALCULATION OF DISCHARGE AND VELOCITY OF DISCHARGE FOR A CIRCULAR ORIFICE

For gauge pressure of 100 psi. Δp = 100 psi.

$h = \Delta p/w$, where w 62.4 lb/ft^3 (water)

h = 231 ft.

From reference 21: Obtain C_c, and C_v.

$V = C_v \sqrt{2gh}$ = velocity of jet

$A_c = C_c A$ = area of vena contracta.

A = area of orifice

$Q = A_c V$ = flow rate

D(in)	C_c	C_v	$A(in^2)$	$A_c(in^2)$	V(ft/sec)	$Q(ft^3/sec)$
.010	.67	.63	$.78\times10^{-4}$	$.522\times10^{-4}$	77	2.79×10^{-5}
.015	.67	.63	1.9×10^{-4}	1.27×10^{-4}	77	5.35×10^{-5}
.505	.66	.62	.198	.133	75.5	6.97×10^{-2}

CALCULATION OF RESONANT FREQUENCY FOR AN 8.2 INCH TUBE CLOSED AT ONE END

$f = (2n + 1)c/4l$

Where: f = frequency, n = any interger, c = velocity of sound, and l = corrected length of pipe.

c = 1110 ft/sec; l = 10 inches

$f = 12\times1110\,(2n + 1)/40 = 666n + 333$

For n = 1,2,3: f = 999, 1665, and 2331

c varies with humidity. Thus these values are approximate.

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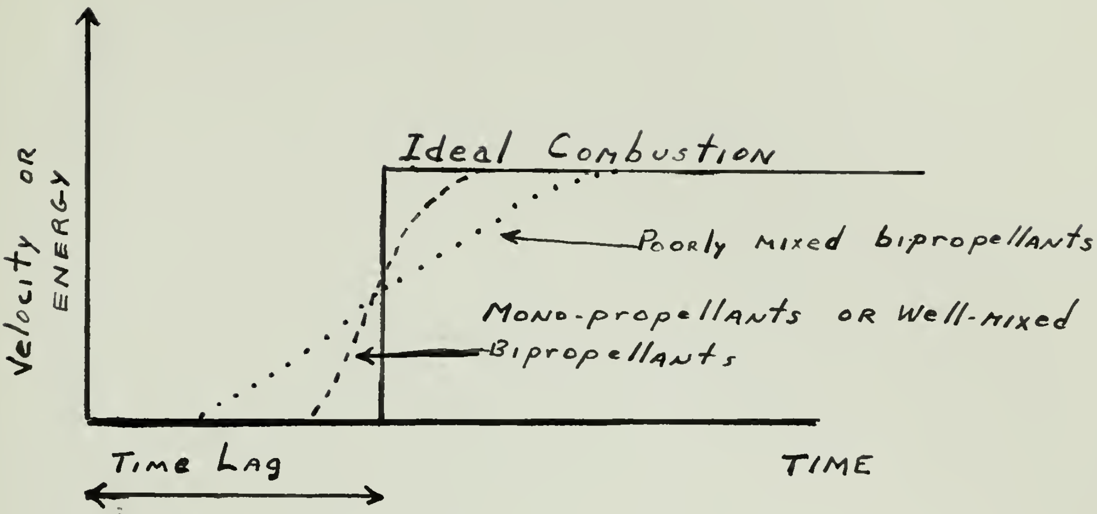


Figure 1.

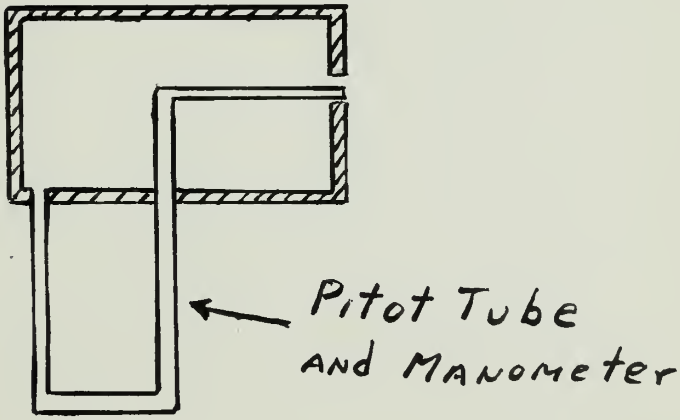


Figure 2.

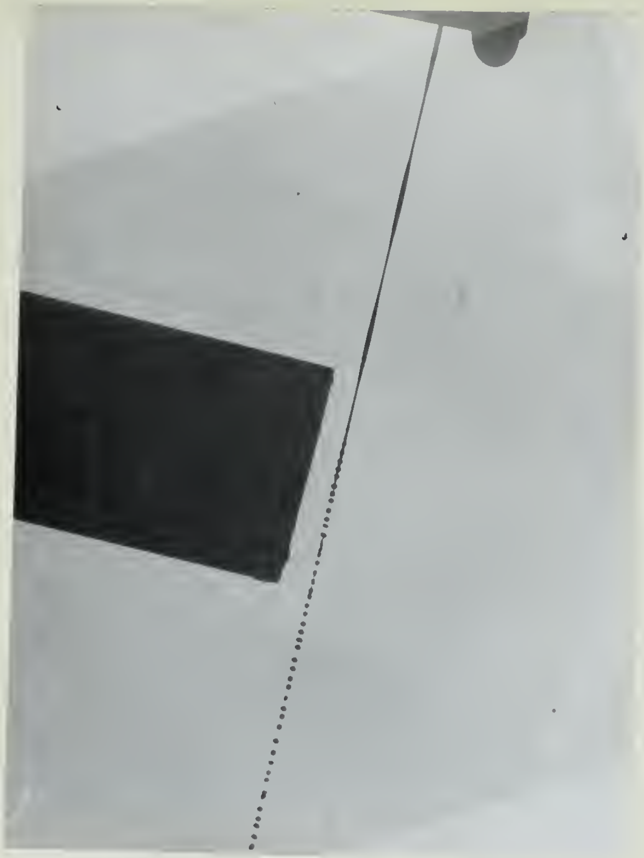


Figure 3.

Figure 4

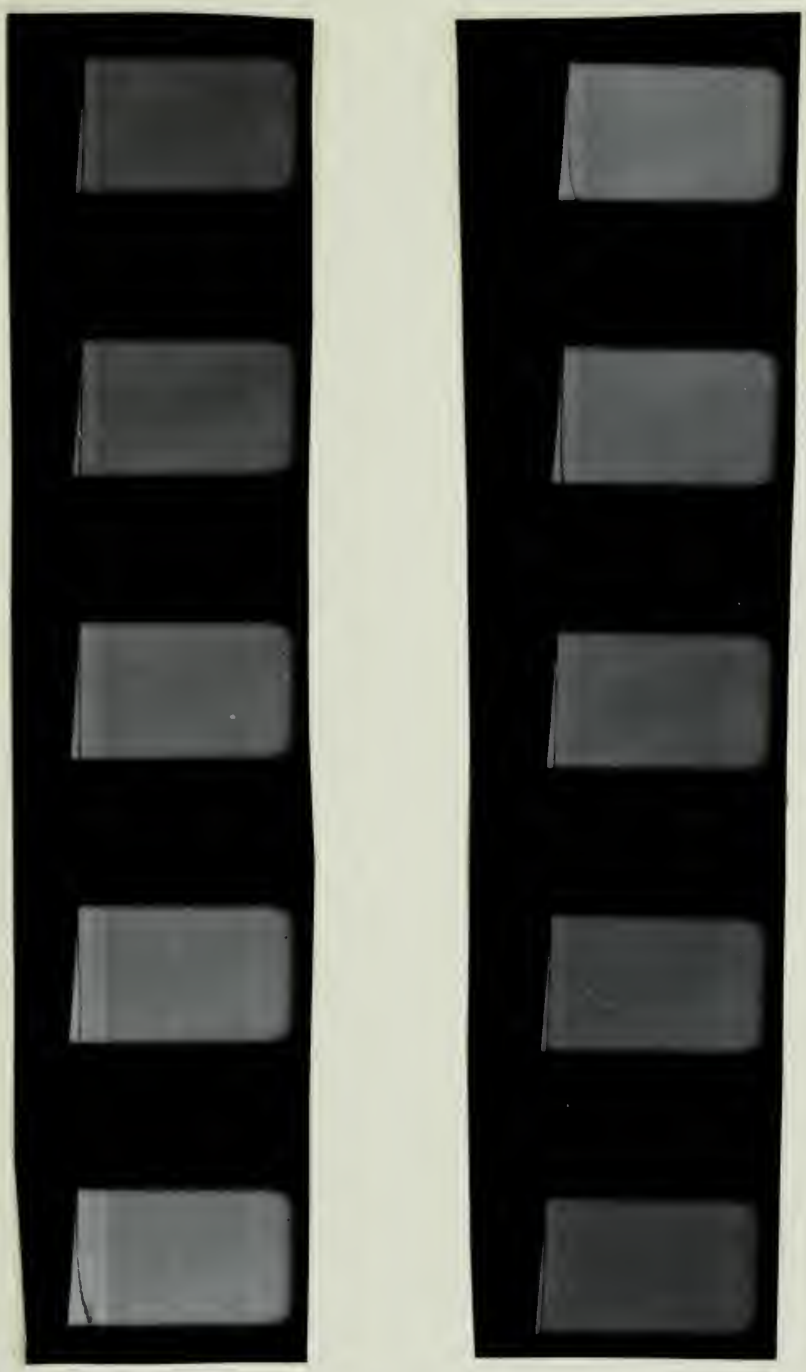


Figure 5.

Figure 6.

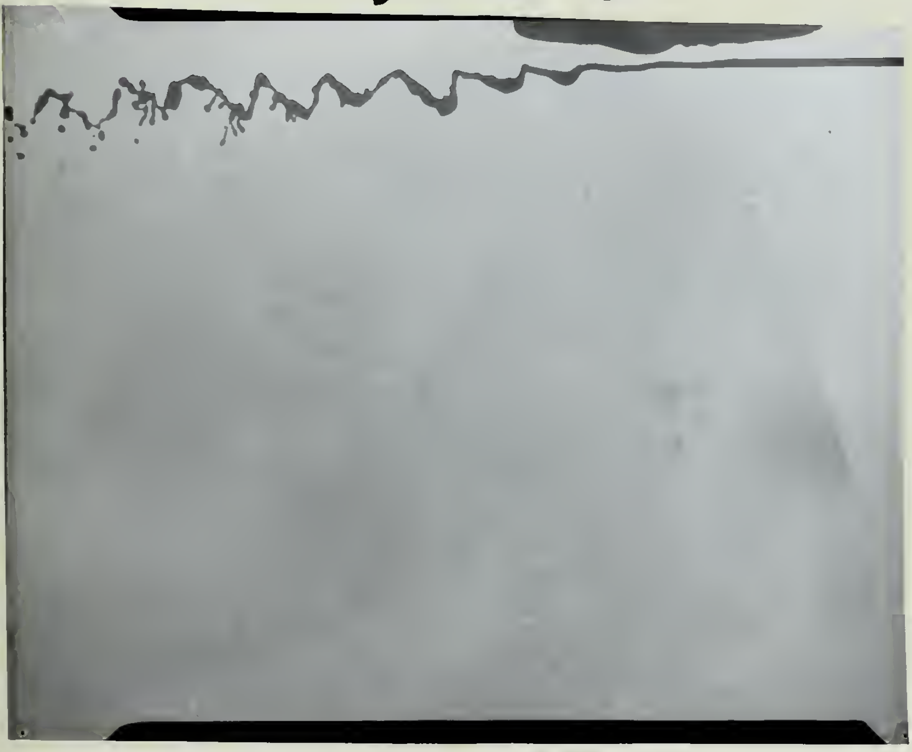
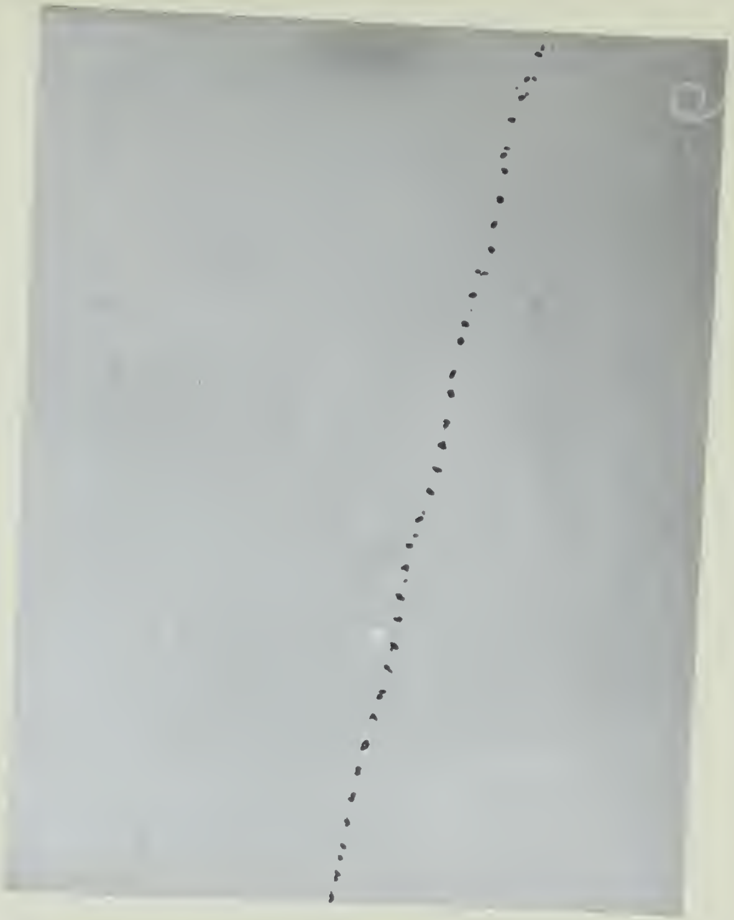


Figure 7.

Figure 8.



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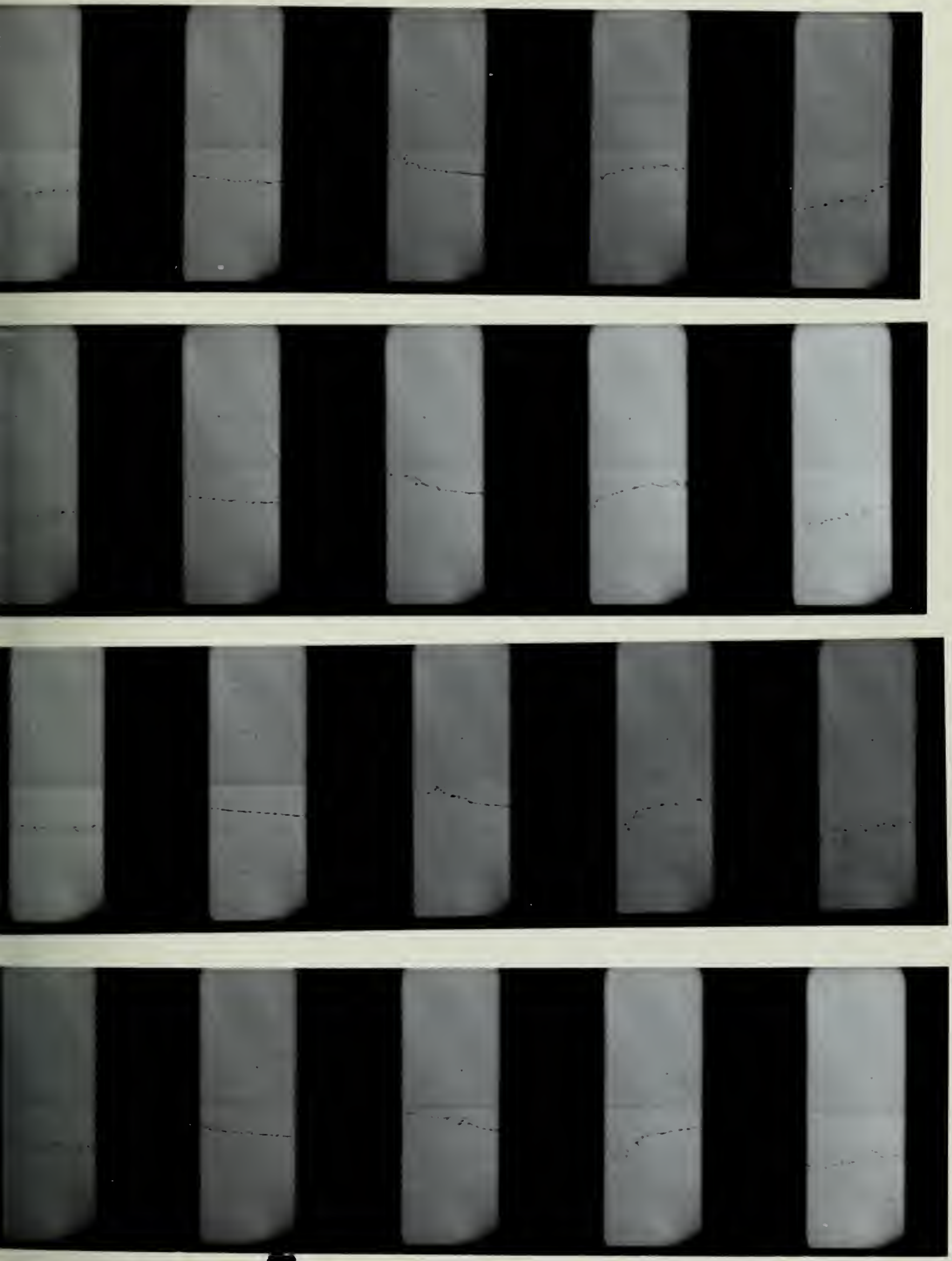

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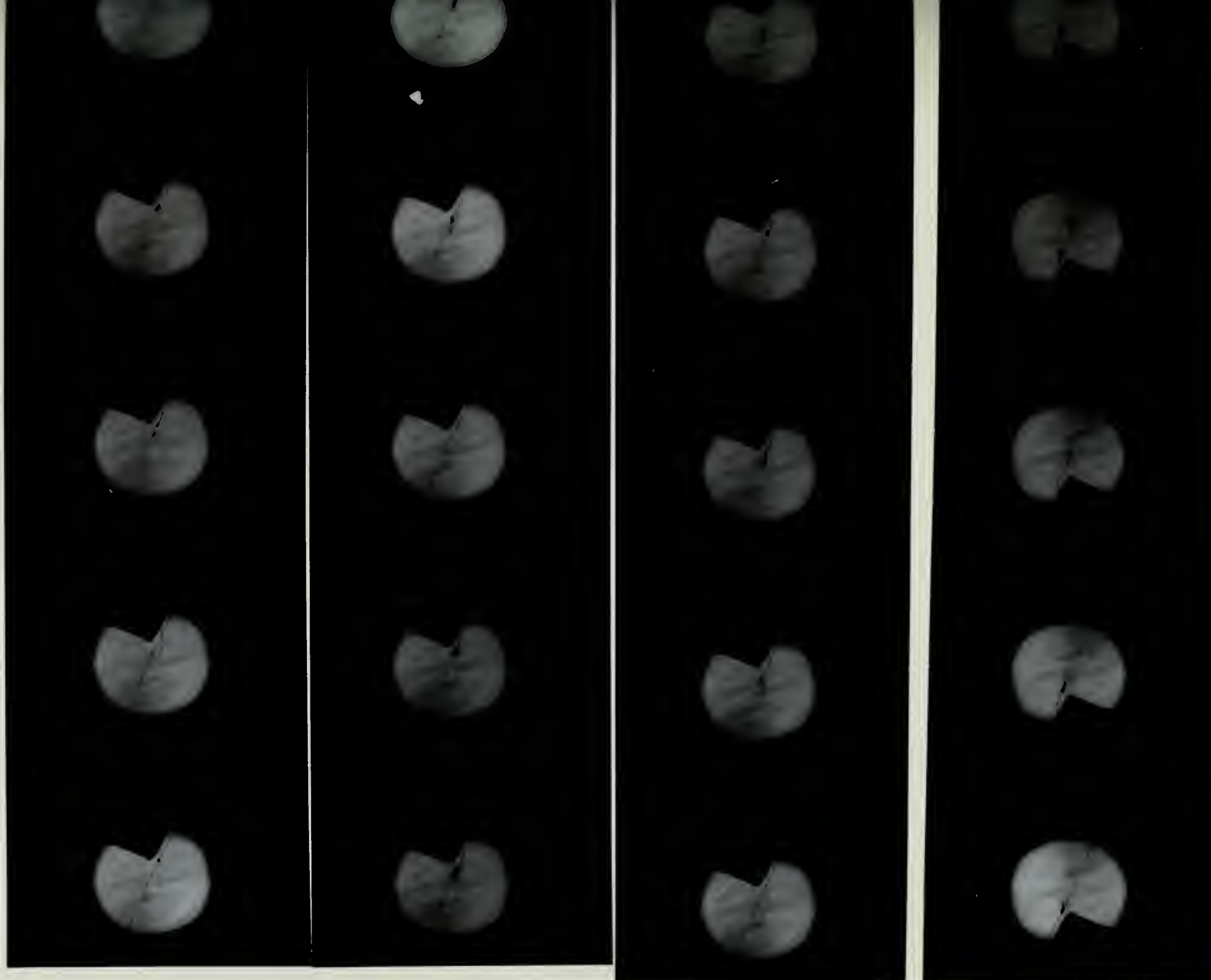

Figure 12.